HYDRAULICS OF TERRACE INTAKE RISERS WITH ORIFICE PLATES

by

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Introduction

It has been estimated that over 36 million hectares (90 million acres) of cropland in the United States could be more effectively protected from runoff and erosion damage through the use of well designed and maintained terrace systems (Schwab et al., 1981).

As technology has advanced, terrace design has been scientifically adapted to the hydrologic and erosion control needs of the treated area. Pipe outlet terraces were known in the early 1900s, but the present modern version was developed in Iowa in the 1960s (Schwab et al., 1981). Today, in some areas, virtually all terraces are constructed with underground outlets. However, few studies have been made regarding the discharge capacity of terrace risers in combination with bottom orifice plates. A laboratory experiment was planned as a starting point of development in this area.

The objectives of this experimental study were to:

1. extend the former research on the discharge-depth relationship of the risers to a lower discharge and to a wider range of conditions

2. experimentally determine discharge-depth curves for each of three different risers in combination with three different sizes of bottom orifice plates

3. compare the experimental data against currently used design criteria

4. develop equations to describe the discharge-depth relationships generated in the laboratory for different riser and orifice plate combinations.

Review of Literature

Underground conduits or outlets are used to dispose of runoff from terraces or from earth embankments used to stabilize natural depressions on unterraced land (Beasley et al., 1984). Over one-half of the terraces installed in Iowa, Illinois, and Missouri use underground outlets (Caldwell, 1985).

Schwab et al. (1981) and Beasley et al. (1984) recommended that the runoff volume for level, pipe outlet and conservation bench terraces be based on a 10-year, 24-hour duration storm.

Linderman et al. (1976) studied the riser intake design for settling basins in feedlots. For calculating the discharge through a riser intake from a basin, they empirically derived equations for risers with 16-mm holes of various spacings ranging from 20 mm through 40 mm.

Discharge Through Side Orifices

As a starting point of theoretical analysis, a simple structure was considered. The riser head, a length dimension measured vertically, is the total energy of the flow per unit weight of water and, by the Bernoulli theorem, is the sum of the potential head, the pressure head, and the velocity head.

Bos (1976) described the flow of water through an orifice by an illustration shown as Figure 1. Water approaching the orifice with a relatively low velocity, passes a zone of accelerated flow, and issues from the orifice as a contracted jet. After passing through the

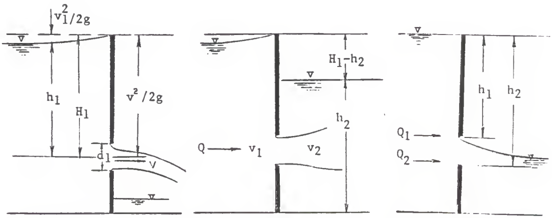
orifice, the flow can have two possible results depending on the outlet condition. If the flow discharges freely into the air above the downstream water surface, it is known as free discharge.

For the free discharging orifice shown in Figure 1.a, assuming that $h_1 >> d_1$ then the pressure in the jet is atmospheric. Applying Bernoulli's theorem yields:

$$H_1 = (h_1 + \frac{v_1^2}{2g}) = \frac{v^2}{2g} \tag{1}$$

Hence:

$$v = \sqrt{2gH_1} \tag{2}$$



a. Free Discharge b. Submerged Discharge c. Partially Submerged

Figure 1. Conditions of Flow through an Orifice (after Bos, 1976)

This relationship between v and $\sqrt{H_1}$ was first derived experimentally in 1643 by E. Torricell. If a discharge coefficient C_e is introduced to correct for the upstream velocity head and the jet contraction, the discharge can be described as:

$$Q = C_e A \sqrt{2gh_1} \qquad (3)$$

where:

C_e is called the effective discharge coefficient

If the orifice discharges under water, it is said to be a submerged orifice. Flow of water through a submerged orifice is illustrated in Figure 1.b.

Assuming Bernoulli's theorem is applicable in this case,

$$H_1 = \left(\frac{P}{\rho g} + z + \frac{v^2}{2g} \right)_1 = \left(\frac{P}{\rho g} + z + \frac{v^2}{2g} \right)_2 \qquad (4)$$

Since:

$$\left(\frac{p}{\rho g} + z \right)_2 = h_2,$$

Hence:

$$v_2 = \sqrt{2g} \left(H_1 - h_2 \right).$$

Using a similar argument to that applied in deriving Equation 3, the total discharge through a submerged orifice is:

$$Q = C_e A \sqrt{2g \left(H_1 - h_2\right)} \qquad (5)$$

Merriam and Keller (1978) suggested that C_e varied from 0.61 to 0.63 for sharp edged orifices which exist for holes drilled in flat plates. Other investigators like Beasley et al. (1984) assume the coefficient of discharge to be approximately 0.6. However, it is important to note that in this study, the orifices on the riser are holes or slots perforated in a curved surface instead of a flat surface.

Visser et al. (1986) studied this specific case to calibrate the discharge coefficient. They set up a model with a section of 152-mm (6-in.) cast acrylic tubing center drilled with a 25.4-mm (1-in.) diameter hole. The results indicated that a round hole in a curved surface has a discharge coefficient ranging from 0.70 to 0.73 which is about 20% larger than the value of 0.6 for the flat surface as previously described.

In this research, the phenomenon of water discharge through the riser can be more complicated. In addition to the two conditions stated above, there is another condition when the down stream surface is situated between the upper and lower edge as shown in Figure 1.c.

For calculating the discharge of the partially submerged orifice, it is more convenient to separate the downstream discharge into 2 parts. The discharge above the downstream water surface, Q_1 ,was taken as a common free orifice and the discharge below the downstream surface, Q_2 ,was taken as a completely submerged orifice case. The discharge Q, is then the sum of these 2 parts, thus:

$$Q = Q_1 + Q_2 = C_1\sqrt{2g} \int b\sqrt{z}\, dz + C_2 a \sqrt{2g\,(h + h_a)} \qquad (6)$$

where b and a are the upper and lower part of orifice area below the down stream water surface respectively. The discharge coefficients C_1 and C_2 , have values of about 0.62 and 0.58 (Wong, 1971).

The existing riser design formulae are more precise and more practical for use in field conditions. An equation for calculating the required number of holes was derived by Beasley et al. (1984) The number of equally spaced holes based on SI units is:

$$N = \frac{0.56\ Q}{a\sqrt{H}} \qquad (7)$$

where:

N = number of holes

Q = peak flow through the riser, m^3 /s

a = area of each hole, m^2

H = maximum depth of water in the terrace channel, m

Visser (1986) derived Equation 8 to determine the discharge capacity at any given head:

$$Q = \frac{2}{3}\, c\ a\ n \sqrt{2g}\ H^{3/2} \qquad (8)$$

where:

Q = discharge

a = area of each orifice

c = orifice discharge coefficient

n = holes per unit depth

g = acceleration of gravity

H = total head

The mathematical proof is as follows:

$$dQ = c\ dA\ (2gh)^{0.5}$$

$$dA/dh = a\ n$$

$$dA = a\ n\ dh$$

$$dQ = [c\ a\ n\ (2g)^{0.5}]\ h^{0.5}\ dh$$

Integrating from h = 0 to h = H yields:

$$Q = [c\ a\ n\ (2g)^{0.5}]\ H^{1.5}/1.5$$

which simplifies to Equation 8.

The Soil Conservation Service (1979) uses Equation 9 for computing the discharge capacity of a riser:

$$Q = c\ A\ \sqrt{2g(0.7)H} \qquad (9)$$

The notations have the same meaning as Equation 8, except for "A", which represents the total area of all orifices. It was assumed that free discharge always prevails. In practice, the discharge capacities

would decrease due to partially submerged flow.

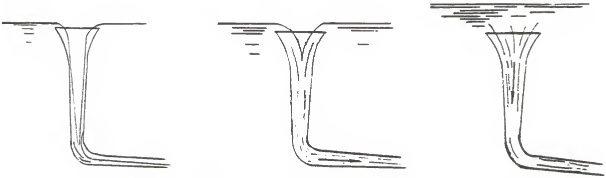
Discharge through Drop Inlet

The flow in the conduit from upslope terraces must be controlled so that there is no excess hydraulic head under a lower terrace causing water to flow up through the riser, which could result in the terrace overtopping (Schwab et al., 1981). However, as Beasley et al. (1984) pointed out, achieving flow control with the outlet conduit may not always be economical. If flow control is achieved with a conduit, pipe size will increase for each terrace unless the ground slope increases enough to allow the same pipe size to carry more flow below the second and succeeding terraces.

Therefore, based upon economic considerations, the conduit size should be minimized. An orifice plate is utilized to achieve this purpose (Beasley et al., 1984). The orifice for pipe outlet terraces is usually selected so that the runoff from the design storm will be removed in a time period of 48 hours or less.

The discharge through a drop-inlet spillway is shown in Figure 2. At low heads, the crest of the riser controls the flow, the vertical transition beyond the crest will flow partly full and the flow will cling to the sides of the shaft, the discharge is proportional to $h^{3/2}$. As the discharge over the crest increases and equals the capacity of the conduit or conduit inlet, the head will keep rising. Eventually, the overflowing annular nappe becomes thicker, and nappe flow will converge into a solid vertical jet."The point where the annular nappe joins the jet is called the crotch. After the solid jet

crotch and the top of the boil become progressively higher with larger discharges. For high heads the crotch and boil may almost flood out, showing only a slight depression and eddy at the surface"(U.S. Dept. of Interior, Bureau of Reclamation, 1974).



a.Crest-control Flow b.Tube- or Orifice-control Flow c.Full Pipe Flow

Figure 2. Schematic of Discharge through Drop-inlet Spillway.

Until such time as weir flow forms a solid jet, free-discharging weir flow prevails. After the crotch and boil form, submergence begins to affect the weir flow and ultimately the crest will drown out. Flow is then governed either by the nature of the contracted jet which is formed by the overflow entrance, or by the shape and size of the vertical transition if it does not conform to the jet shape. "At this section, the flow becomes proportional to the square root of the total head loss through the structure or the head on the conduit inlet and the orifice or tube will govern for flow" (Schwab, 1981).

Discharge through Bottom Orifice Plate

The discharge through the bottom orifice is similar to the discharge through an opening in the Danïdean tub as shown in Figure 3. The discharge can be determined by Equation 10 which is similar to Equation 3 (Bos 1976):

$$Q = C_d A\sqrt{2gh} \qquad (10)$$

where C_d is the discharge coefficient

For the flat bottom orifice plate, the discharge coefficient is dependent on the coefficient of jet contraction, δ , which is a function of the ratio of the orifice diameter to the riser diameter.

Merriam and Keller (1978) specified the same orifice equation as above for sharp-edged orifices which exist for holes drilled in the plates. In this condition C_d varied from 0.61 to 0.63.

By using the contraction coefficient in the continuity and pressure velocity Bernoulli equation, Bos (1976) cited the following relationship for the discharge coefficient of water flowing through an orifice:

$$C_d = \frac{\delta}{\sqrt{1-\delta^2(\frac{d}{D})^4}} \qquad (11)$$

where:

d is the orifice diameter and D is the inside diameter of the riser

Based upon the boundary geometry, the discharge coefficient C_d has values of 0.620, 0.638 and 0.675 for orifice diameters of 38 mm (1.5 in.), 64 mm (2.5 in.) and 89 mm (3.5 in.) respectively in a 152-mm (6-in.) diameter riser.

The above discharge equation and related coefficient values apply if the orifice is placed at the end of a straight pipe which discharges its jet free into the air.

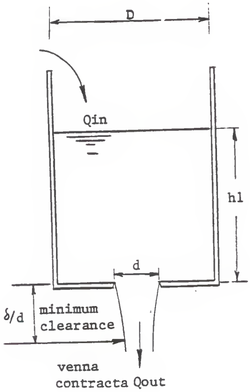


Figure 3. Circular Danïdean tub (after Bos)

Beasley et al. (1984) provided a table which gives the relationship between discharge rate and head for different sizes of circular orifices and riser pipes. The value of discharge rate in cubic feet per second (cfs) was computed with:

$$Q = 0.6A\sqrt{2gH} \tag{12}$$

where:

A = Orifice area in square feet

g = 32.2 ft/sec^2

H = head in ft, is defined as 0.7(water depth in channel) + depth of orifice plate below the ground surface

Beasley et al. (1984) stated that orifices less than 38-mm (1.5-in.) in diameter have severe plugging problems and should not be used. Under field conditions, it is necessary to remove debris from the holes or slots in the intake risers and from the orifice plates to maintain a smooth drainage toward the outlet.

Linderman et al. (1976) compared the capacity of the same riser with 20-mm hole spacing with that of a 75-mm diameter orifice below the riser at the ground level. His results showed that when head, h, is less than 0.65 m, the riser intake capacity determined the flow. When h is greater than 0.65-m, the 75-mm orifice has less capacity than the riser and so restricted the flow. The diameter of the riser was not stated.

Materials and Testing System

Risers and Orifice Plates Tested

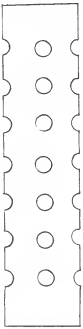
Four different risers and three diameters of bottom orifice plates were tested. All four risers were fabricated from 152-mm (6-in.) diameter, transparent cast acrylic pipe with a wall thickness of 3 mm (1/8 in.). The flow inside the riser was therefore visible.

The Type 1 and Type 2 risers are shown schematically in Figure 4.a. The risers were drilled with four columns of 25.4-mm (1-in.) diameter holes equally distributed along the pipe length. Each column was 90 degrees from the next column. Holes in each column were equally spaced at 102 mm (4 in.) and 64 mm (2.5 in.) for the first and second riser, respectively. Both risers were about 0.9 m (3 ft.) tall.

The Type 3 riser was simply a section of 152-mm (6-in.) diameter cast acrylic pipe with a length of 450 mm (18 in.). The top of the riser was open. A commercially manufactured steel bar-screen was mounted on the top. In addition to maintaining converging flow into the drop inlet, vortex action must be minimized. An anti-vortex plate was employed along the crest in order to minimize the effect from fluctuations of the water surface. The anti-vortex plate was a 3.2-mm (1/8-in) thick aluminum plate with dimensions of 305 mm x 235 mm installed through the bar screen.

A Type 4 riser is shown schematically in Figure 4.b. A section of 0.9 m (3 ft.) long cast acrylic pipe as previously described was cut with slots along the pipe circumference in a spiral fashion. The

(a)



Hole diameter	24.5 mm (1 in.)
Holes row spacing	Type 1, 102mm (4in.)
	Type 2, 64mm (2.5in.)
Holes per unit length	Type 1, 40 Holes/m
	Type 2, 67 Holes/m
Total number of holes	Type 1, 32
	Type 2, 52
Riser Diameter	152.4 mm (6-in.)
Thickness	3.2 mm (1/8 in.)

(b)

Slot size	25x102 mm (1x4 in.)
Vertical spacing	102 mm (4 in.)
Slots per unit length	10 slots/m
Total number of slots	6
Nominal riser Diameter	152.4 mm (6 in.)
Thickness	3.2 mm (1/8 in.)

Figure 4. Descriptions of the Risers
a. Round Hole Risers b. Slotted Riser

slots were 25.4 mm (1 in.) wide and 102 mm (4 in.) long with rounded ends spaced 102 mm (4 in.) on centers.

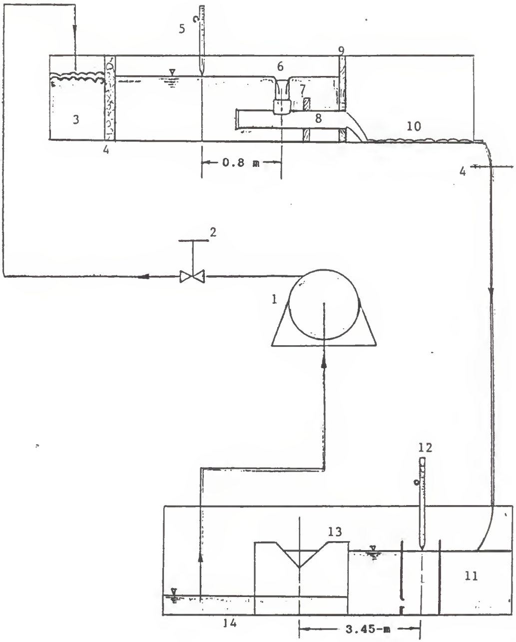
The bottom orifice plates were fabricated from a 6-mm (1/4-in) clear cast acrylic sheet with outside diameter of 152 mm (6 in.) and orifice diameters of 38 mm (1.5 in.), 64 mm (2.5 in) and 89 mm (3.5 in). In combination with risers, the bottom orifice plates were set with the top of plates depressed 89 mm (3.5 in.) and 115 mm (4.5 in.) below the lower edges of the lowest side orifices of the riser for Type 1 (102-mm spacing, round hole) and Type 2 (64-mm spacing, round hole) risers, respectively.

Testing System

A complete flow diagram of the testing system is shown in Figure 5. The research was conducted in the Kansas State University hydraulics laboratory.

Water was pumped from the sump by a horizontal, V-belt driven centrifugal pump. By adjusting the pulley diameter, the pump speed was varied. However, to adjust for different discharges, it was more convenient to fix the pump speed at the minimum and simply adjust the discharge gate valve.

The riser was fitted in a PVC saddle T-joint. Water was directed out by a 254-mm (10-in.) diameter horizontal PVC discharge pipe. The outlet pipe was about 3 m (10 ft) long with one end capped and the other side directed into the lower flume. The discharge pipe had excess capacity allowing free discharge from the riser or orifice.



1.	Pump	8.	12-in Discharge Pipe
2.	Gate Valve	9.	Plywood Brace
3.	Trough	10.	Upper Flume
4.	Baffle	11.	Lower Channel
5.	Riser Head Point Gauge	12.	Weir Head Point Gauge
6.	Riser	13.	Std. V-Notch Weir
7.	Plywood Check Gate	14.	Sump

Figure 5. Schematic of Test System

When the bottom orifice plates were tested, they were set below the riser on the T-joint. Figure 6 shows a riser installed for testing in the flume.

The joints were sealed with rubber gaskets and caulking material. To constrain the outlet pipe, a plywood brace was constructed to support the uplift and side forces acting on the entire length of outlet pipe. The flume is approximately 0.8 m (31 in.) wide and 13 m (39 ft) long with sides 1.2 m (4 ft) high. Due to the discharge pipe and T-joint, the maximum head for testing riser was 0.79 m from datum. The slope of the flume was adjusted to 1% during the complete experiment.

After discharging from the outlet PVC pipe, water flows along the upper flume and falls about 2 m (6 ft) down into a lower returning channel. The lower channel is about 0.86 m (34 in) wide with finished concrete sides and bottom and slope of 0.5%.

At the downstream end of the channel, a 90-degree, sharp-crested, V-notch weir was constructed with a 6-mm (1/4-in) steel sheet perpendicular to the sides and bottom of the channel. The invert of the weir was 0.3 m (12 in.) above the channel bottom and the distance from the top edge of the weir to its invert was about 0.3 m (12 in.). The V-notch weir in the stream channel is shown in Figure 7. The downstream edge of the notch was bevelled at an angle of approximately 60 degrees with the surface. The seams between the weir plates and sides and bottom were caulked to stop leakage. Finally, the water returned to the sump after flowing over the weir.

Figure 6. Side View of Open-riser with Bar Screen and Anti-vortex Plate installed in Flume

Figure 7. Relative Location of the V-notch Weir and Point Gauge

Head and Discharge Measurement

The riser head and the weir head were measured almost simultaneously. It was assumed that all the measurements were made under steady-state flow conditions. To have steady-state flow, it took from 20 to 50 minutes after the discharge valve was adjusted, depending on the rate of discharge water, the riser and also the sizes of orifice plates tested. For some combinations, such as the Type 3 (open-top) riser without orifice plate and with higher discharge for instance, the equilibrium condition could never be reached due to the vortex existing at the riser inlet causing unstable flow.

The Weir Head and Discharge

The discharge of the riser and bottom orifice plate was determined indirectly from the triangular weir discharge capacities which were calculated from the weir equation. It was assumed that the weir head was read when steady-state flow occurred.

The weir head was defined as the the level of water surface relative to the level when water initially flowed across the bottom of the V-notch. The head at which water initially flowed was found to be 0.3 mm above the bottom of the V-notch. At a weir head of 41 mm, the lowest measured, this 0.3-mm difference in head produced a 1.6 % difference in computed discharge. This difference was assumed insignificant in this study.

A point gauge was set 3.45 m (11.3 ft) upstream from the weir. The weir head was then measured by this point gauge in a stilling

well which was used to reduce the water fluctuation to a minimum. Differences in measurements due to the distance from weir surface to point gauge were calculated with maximum value of 0.3 mm for different discharges and distances and were assumed negligible.

The discharge from the riser and orifice plate through the standard triangular sharp-crested weir can be measured and calculated by substituting the weir head into the weir equation (Bos, 1976) as follows:

$$Q = C_e \frac{8}{15} \sqrt{2g} \tan\left(\frac{\theta}{2}\right) h_e^{\frac{5}{2}} \tag{13}$$

where:

Q = weir discharge, mm^3/s (ft^3)

C_e = discharge coefficient

θ = angle of notch

g = acceleration due to gravity

h_e = effective weir head, mm (ft)

while:

$$h_e = h_1 + k_v$$

where:

h_1 = the measured weir head

k_v = the notational vertical displacement of the vertex due to surface tension and viscosity, 1 mm (0.003 ft).

A corresponding illustration for above formula is shown in Figure 8. The V-notch sharp-crest weir with 90-degree notch was selected because of availability and its accurate results. To use the standard value of C_e in this equation, some limitations were satisfied. Table 1 shows a comparison of the existing weir parameters and the limitations listed by Bos (1976). Table 2 shows the standard value of the discharge coefficients for different heads.

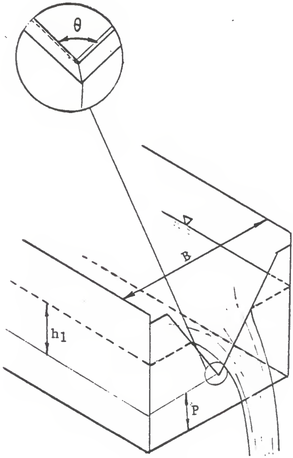


Figure 8. Schematic of V-notch Weir.

Table 1. V-notch Weir Equation Limitations (after Bos, 1976)

Variable	Limits	Value Used
$\frac{h_1}{P}$	< 1.2	< 0.63
$\frac{h_1}{B}$	< 0.4	< 0.22
h_1	0.05m - 0.6m	0.05m - 0.25m
P	> 0.10m	0.3m
B	> 0.60m	0.86m
Weir Tailwater	below the vertex	yes

Table 2. Discharge Coefficients for 90 degree V-notch Weir with P value of 0.3 m (after Bos, 1976)

Weir Head (mm)	Weir Head (ft)	Weir Coefficient
61	0.20	0.578
91	0.30	0.578
122	0.40	0.578
152	0.50	0.579
183	0.60	0.580
198	0.65	0.581
213	0.70	0.582
229	0.75	0.584

The Riser Head

The riser head was defined as the the level of water surface relative to the level when water initially flowed across the very bottom row of the side orifices of the riser. The error of head measurements due to surface tension was assumed negligible. This head was measured by another point gauge set 0.8 m (2.7 ft) apart from the center line of the riser. The precision of the gauge was 0.001 ft.

Orifice Head

In this study, all four risers were first tested without bottom orifice plates, then all except for the Type 4 (slotted) riser were tested in combination with 3 different diameters of orifice plates.

The head on the bottom orifice plate was defined as the difference in elevation of the water surface outside the riser and that of the upper surface of the circular orifice plate. In summary, 12 combinations were tested, and were classified tests 1 through 12. A list of these tests is shown in Table 3.

Table 3. List of Experiments

Experiment	Riser Used	Orifice Plate
1	102-mm spacing, Round Hole	None
2	102-mm spacing, Round Hole	89-mm
3	102-mm spacing, Round Hole	64-mm
4	102-mm spacing, Round Hole	38-mm
5	64-mm spacing, Round Hole	None
6	64-mm spacing, Round Hole	89-mm
7	64-mm spacing, Round Hole	64-mm
8	64-mm spacing, Round Hole	38-mm
9	Open-Top, with Bar Screen and Anti-vortex Plate	38-mm
10	Open-Top, with Bar Screen and Anti-vortex Plate	64-mm
11	Open-Top, with Bar Screen and Anti-vortex Plate	89-mm
12	Slotted	None

Note: Descriptions of risers are shown in Figure 4 on page 15.

Results

The data collected in this experiment are given in Tables 9 through 20, in the Appendix. The riser head in column 1 represents the water stage. The weir depths, taken simultaneously, are listed in column 2. By substituting the corresponding weir discharge coefficients, C_e, in column 3 and weir depths, the weir discharge in column 4 was calculated with Equation 13.

The depth shown in millimeters is actually converted from the readings taken in feet with the point gauge. Again, for each riser depth there is a corresponding discharge to represent it. For risers with bottom orifice plates, it is assumed that at small heads, the discharge is controlled by the riser and is proportional to $h^{3/2}$. As the discharge increases, the control shifts to bottom orifice control and the discharge is proportional to the square root of the depth.

Since the main outlet pipe had a diameter of 254 mm (10 in.), much greater than the bottom orifice diameter, there was always free outflow. The pipe control situation never existed in this study. The relationships for each riser-orifice plate combination were determined by regression analyses of discharge versus square root of riser head within the bottom orifice control range.

The data sets for each combination can therefore be described by the best-fit equation. The best-fit equations were plotted with the same scale superimposed on the experimental data points. The correlation coefficients, R^2, were computed to describe how well the equations fit the data. These values are given in Table 4.

Table 4. Equations for Head-Discharge Relationships

Riser	*Head Range (mm)	Orifice	Equation	R^2
102-mm Spacing, Round Hole	27-352	None	$Q = 0.0013\ H^{3/2} + 0.65$	0.998
102-mm Spacing, Round Hole	215-427	89-mm	$Q = 0.886\ H^{1/2} - 8.65$	0.997
102-mm Spacing, Round Hole	110-778	64-mm	$Q = 0.308\ H^{1/2} - 0.73$	0.993
102-mm Spacing, Round Hole	20-442	38-mm	$Q = 0.094\ H^{1/2} + 0.33$	0.991
64-mm Spacing, Round Hole	34-488	None	$Q = 0.002\ H^{3/2} + 1.27$	0.999
64-mm Spacing, Round Hole	95-581	89-mm	$Q = 0.70\ H^{1/2} - 3.69$	0.991
64-mm Spacing, Round Hole	92-559	64-mm	$Q = 0.32\ H^{1/2} - 0.50$	0.991
64-mm Spacing, Round Hole	28-715	38-mm	$Q = 0.12\ H^{1/2} - 0.06$	0.98
Open-Top	73-195	89-mm	$Q = 0.33\ H^{1/2} + 9.24$	0.973
Open-top	49-415	64-mm	$Q = 0.21\ H^{1/2} + 4.23$	0.999
Open-top	40-284	38-mm	$Q = 0.08\ H^{1/2} + 1.54$	0.991
Slotted Riser	81-395	None	$Q = 0.001\ H^{3/2} + 0.27$	0.999

* Limit use of equations:

1/ Equations for risers without orifice plate are obtained based on the assumption that only riser-control flow exists within entire head range tested as shown in column 2.

2/ Equations for risers with orifice plates are obtained based on the assumption that orifice-control flow exists within the head range as shown in column 2.

Based upon the results, the discharge-depth relationships are plotted in Figures 9 through 11. For each of the four risers without and with the three different sizes of orifice plates. Figures 12 through 15 compare the discharge capacities of the different risers with the same orifice plates.

The head on the circular orifice plate was measured outside the riser. However this measurement may not be the true head of the orifice plate, since the head outside the riser is definitely greater than the inside head - the true head. Unfortunately, the flow inside the riser is relatively turbulent and the level is impossible to ascertain directly by measuring with the point gauge. To determine this true head, the pressure head may be a valuable reference for a pressure gauge or piezometer. Again, the riser head was read when the water surface was stabilized, thus the head at that moment was actually the head that makes the bottom orifice discharge at the same rate as water flows into the riser.

One of the research objectives was to compare the experimental data against current design criteria, Equation 8 and Equation 9. The least-squares method was used to determine the discharge coefficients. Different discharge coefficients were substituted into Equation 8 and the sum of squares computed. The discharge coefficients, which yielded the least sum of squares were selected as 0.75 for the 25.4-mm diameter round hole risers and 0.60 for the slotted riser, respectively.

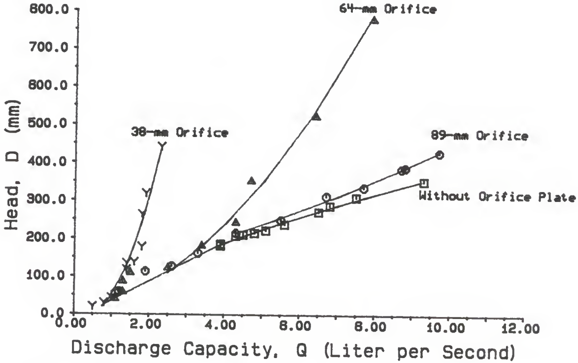


Figure 9. Depth-Discharge Relationship for 102-mm Spacing, Round Hole Riser

Note that curves represent the regression equations within the bottom orifice control ranges.

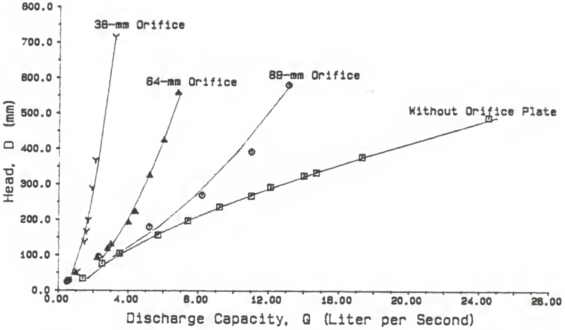


Figure 10. Depth-Discharge Relationships for 64-mm Spacing Round Hole Riser

Note thet curves represent the regression equetions within the bottom orifice-control renge.

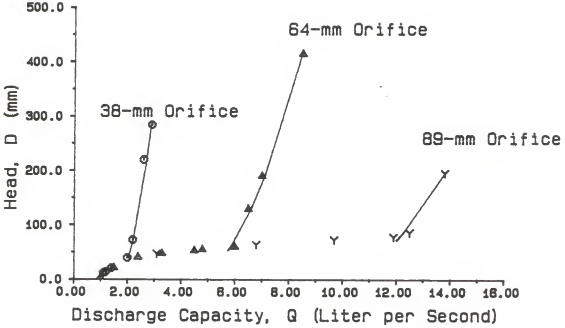


Figure 11. Depth-Discharge Relationships for Open-top Riser with Bar Screen and Anti-Vortex Plate

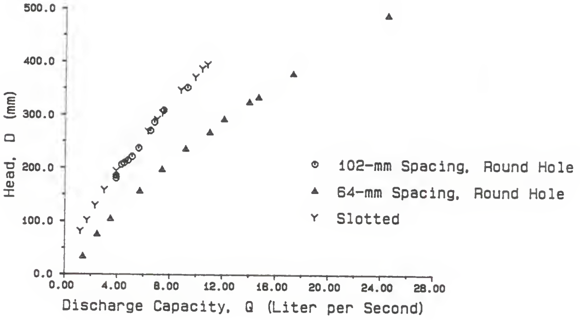


Figure 12. Discharge Comparison for Risers without Orifice Plate

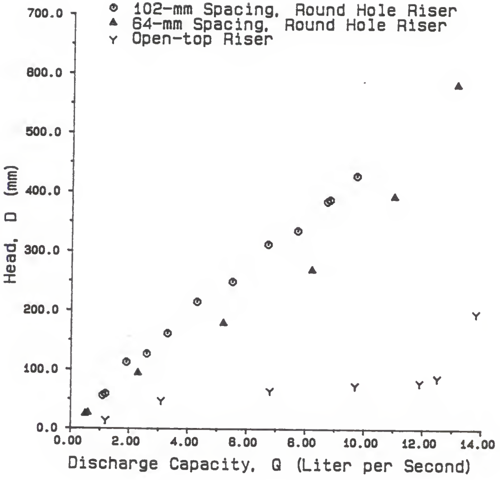


Figure 13. Discharge Comparison for Risers with 89-mm Orifice Plate

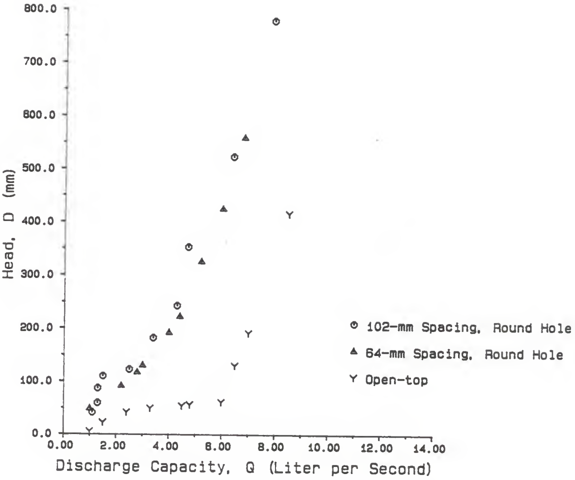


Figure 14. Discharge Comparison for Risers with 64-mm Orifice Plate

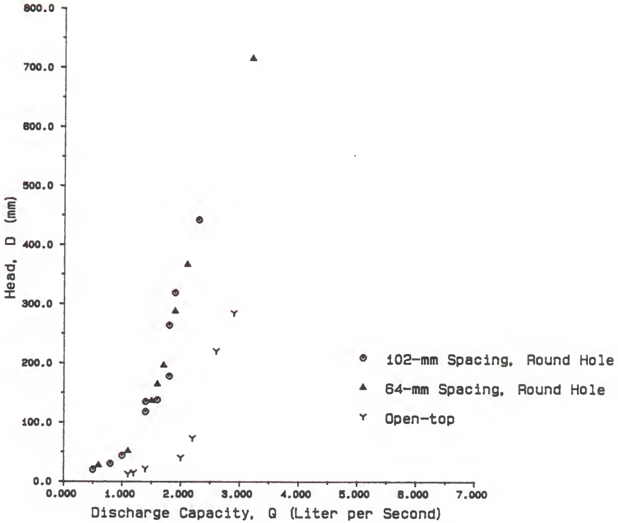


Figure 15. Discharge Comparison for Risers with 38-mm Orifice Plate

Tables 5 through 7 compare the experimental data with discharges predicted by Equation 8 and Equation 9 using the selected discharge coefficients. The head-discharge curves are plotted in Figures 16 through 18.

Table 5. Comparison of experimental data with predicted value by design equations for 102-mm spacing, round hole riser

Riser Head (mm)	Weir Disc. (L/s)	Eq. 9 Disc. (L/s)	Eq. 8 Disc. (L/s)
27	0.9	0.20	0.19
182	3.9	3.60	3.40
187	3.9	3.76	3.54
208	4.3	4.41	4.16
211	4.5	4.51	4.25
216	4.8	4.67	4.40
223	5.1	4.90	4.62
239	5.6	5.44	5.12
272	5.5	6.61	6.22
288	6.8	7.20	6.78
310	7.5	7.04	7.58
353	9.3	9.78	9.21

(Orifice Discharge Coefficient = 0.75)

Table 6. Comparison of experimental data with predicted value by design equations for 64-mm spacing, round hole riser

Riser Head (mm)	Weir Disc. (L/s)	Eq. 9 Disc. (L/s)	Eq. 8 Disc. (L/s)
35	1.36	0.58	0.46
77	2.47	1.94	1.54
106	3.52	3.14	2.50
158	5.71	5.75	4.57
199	7.40	8.14	6.48
238	9.16	10.66	8.49
269	10.95	12.82	10.19
294	12.12	14.65	11.65
326	14.00	17.11	13.61
335	14.67	17.83	14.18
379	17.27	21.47	17.07
489	24.46	31.49	25.04

(Orifice Discharge Coefficient = 0.75)

Table 7. Comparison of experimental data with predicted value by design equations for slotted riser

Riser Head (mm)	Weir Disc. (L/s)	Eq. 9 Disc. (L/s)	Eq. 8 Disc. (L/s)
82	1.22	1.32	1.00
103	1.73	1.84	1.44
130	2.33	2.52	2.01
159	3.01	3.42	2.73
196	4.11	4.61	3.72
271	6.30	7.54	6.00
293	7.11	8.51	6.83
305	7.43	9.00	7.22
348	8.92	11.01	8.73
372	9.93	12.12	9.73
387	10.54	12.92	10.32

(Orifice Discharge Coefficient = 0.60)

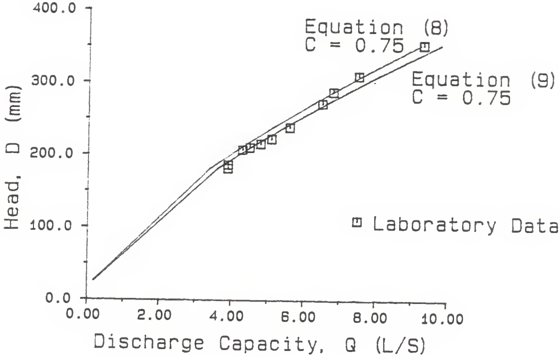


Figure 16. Discharge Comparison of Laboratory Data and Existing Equation for 102-mm Spacing, Round Hole Riser

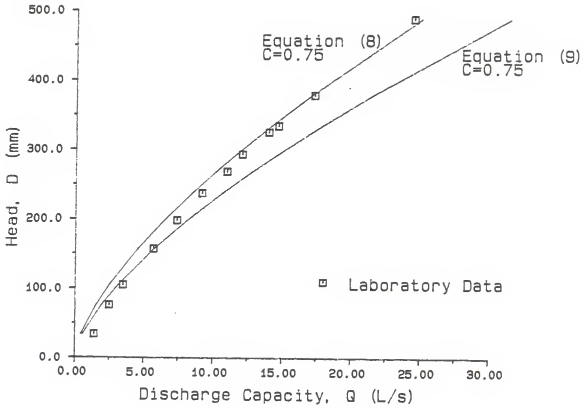


Figure 17. Discharge Comparison of Laboratory Data and Existing Equations for 64-mm Spacing, Round Hole Riser

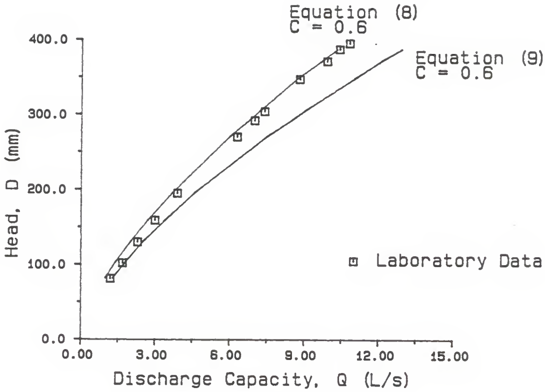


Figure 16. Discharge Comparison of Laboratory Data and Existing Equations for Slotted Riser

Discussion

Comparison of Discharge Capacity

Figures 12 through 15 compare the discharge capacities of Type 1, Type 2 and Type 3 risers in combination with various sizes of orifice plates. It can be easily seen that the Type 2 (64-mm spacing, round hole) riser discharges more than Type 1 (102-mm spacing, round hole) riser. The differences are not as significant for the smaller orifice plate as the larger one. For example, when the 36-mm (1.5-in.) orifice plate was used, the discharges of Type 1 and Type 2 are fairly close but the two curves deviate when the 89-mm (3.5-in.) orifice plate was used. This is because that for a greater discharge, there is a corresponding greater variance of "true-orifice-head" influenced by the greater orifice area. The discharge capacity of the Type 1 and Type 4 riser are fairly close. Thus, the order of discharge capacity for the three risers is: Type 2 > Type 1 $\simeq$ Type 4. The difference in discharge capacities is caused by both inlet area and orifice discharge coefficient.

To evaluate the discharge from the risers without orifice plate, the experimental data were compared with Equations 8 and 9. The discharge comparisons are shown in Tables 5 through 7. Figures 16 through 18 are used to compare the test data with discharge calculated by the currently used design equations, Equations 8 and 9. Both theoretical equations were drawn in the same scale with the data points. Using a discharge coefficient of 0.75, the discharge through both the 25.4-mm round hole risers can be closely predicted by Equa-

tion 8 at higher stages and Equation 9 at lower stages. The discharge through the slotted riser can be accurately predicted by Equation 8 with a discharge coefficient of 0.6.

Riser-Control Flow and Orifice-Control Flow

In this study of the bottom orifice plates, the head-discharge equations derived were based on a theoretical analysis. From the shape of the head-discharge relationship for all three risers tested in combination with three sizes of orifice plates, the laboratory data support the hydraulic theory. At low head, the relationships do follow the no bottom orifice curve which gives a sharp increase in discharge capacity as the head increased slightly. With the results obtained from regressions, for risers without bottom orifice plates, the R^2 values are nearly equal to 1. Thus the relationship:

$$Q \propto H^{3/2} \tag{14}$$

was apparent.

As the orifice head increased, the curves diverted upward from different points on the no bottom orifice curve. This means that there are different points of transition from riser-control flow to orifice-control flow for different sizes of orifice plates. As the flow shifted to orifice control, an increase in head results in only slight increase in discharge, and the relationship:

$$Q \propto H^{1/2} \tag{15}$$

was marked in this condition. It was observed that rising turbulence, a sudden change in the flow speed and a change in sound resulted at the transition from riser contorl to bottom orifice control stages. The more abrupt the transition, the more evident this phenomenon.

For a small bottom orifice, the head-discharge curves are steeper and changed more rapidly from riser-control flow to orifice-control flow than for a large orifice. In the laboratory, it was observed that heads changed more sharply for the 38-mm (1.5-in.) orifice plate than the 89-mm (3.5-in.) orifice plate under the same discharge. This is because the discharge is proportional to the ratio of the total inlet area of the riser over the bottom orifice area.

It is interesting to tabulate the divert-point, the points of transition for the three different risers as shown in Table 8. From the table, evidently the riser with high discharge changes riser-control flow to orifice-control flow at a lower stage which still yields a higher discharge, and vice versa. This can be explained by the greater discharge yielded by the riser itself at the same head and the transition is actually determined by the discharge. For example, the 64-mm spacing, round hole riser may not need as much head to yield the discharge required for transition.

Regression Equations

The regression equations constructed for each riser without or with each orifice plate are based on the analysis of hydraulic theory. In the beginning, the simulation of the riser-orifice combination model is assumed reliable for the drop-inlet spillway. Table 4 gives

a list of these equations, range of heads tested and the correlation coefficients, R^2 .

Table 8. Points of Transition from Riser-Control to Bottom Orifice-Control, (Discharge, L/s , Depth, mm)

	Orifice Diameter (mm)		
Riser	38	64	89
102-mm spacing, Round Hole	(0.8 , 90)	(1.5 , 140)	(3.8 , 200)
102-mm spacing, Round Hole	(1.1 , 50)	(2.7 , 110)	(5.0 , 160)
Open-Top	(2.0 , 40)	(6.0 , 60)	(12.2 , 60)

First, the regressions were run for Type 1, Type 2 and Type 4 risers without bottom orifice plate for discharge, Q, versus head to the three-halves power, $H^{3/2}$. The data for Type 3 riser without orifice could not be evaluated because they were obtained in a fluctuating condition, and both the riser head and weir head could not be measured accurately enough.

Then, the regressions were run for the data over the orifice-control range for discharge, Q, against square root of depth, $\sqrt{H}$. Points below the orifice-control range were omitted in these relation-

ships. For these equations, the intercepts (the constant term) represent the points at which the flow shifted from riser control to orifice control. The R^2 values in the last column indicate how well the models fit the laboratory data.

Again, the equations in Table 4 were derived based upon the theoretical discharge analysis with the laboratory data. It should be noted that these regressed semi-empirical equations may not best fit the laboratory data especially, when the testing conditions such as stages, are changed. However, they provided basic understanding of the head-discharge relationships in this study.

Anti-vortex Plate

The anti-vortex plate was cut from 3.1-mm (1/8-in.) thick aluminum sheet to size of 305 mm x 235 mm. Combined with the Type 3 (open-top) riser, the anti-vortex plate was installed through the steel bar-screen which was first mounted onto the top of the riser.

In this experiment the open-top riser was first tested without installing the bar-screen and anti-vortex plate and induced a marked vortex surrounding the riser top and continual fluctuation of water level. This phenomenon was diminished to rather unobvious when the bar-screen was installed onto the riser. The turbulent conditions became more tranquil. However, the fluctuation of water level still existed at high discharge. The arbitrarily sized anti-vortex plate was added to yield steady conditions. Tests for other sizes of plates may be necessary to solve the vortex problem.

If this type of open-top riser was to be used in the field, an appropriate anti-vortex plate should be used since a vortex can significantly affect the discharge. In addition, the vortex inside and outside the riser can introduce serious lateral vibrations which may loosen the riser joint.

Conclusions

1. For the two circular-hole (Type 1 and Type 2) risers the discharge is closely predicted by Equation 8 at higher stages and Equation 9 at lower stages, using a discharge coefficient of 0.75. The Equation 8 can accurately predict discharges for the slotted riser when a discharge coefficient of 0.6 is used.

2. When different sizes of bottom orifice plates are combined with risers, there are different points of transition from riser-control to bottom orifice control flow. The risers with larger inlet area relative to the bottom orifice area have higher tendency of bottom orifice control flow.

3. The discharge characteristics of risers with different hole spacings combined with a small bottom orifice are similar but deviate when larger orifice plates are used.

4. The open-top riser tends to introduce vortices, which yield unsteady flow conditions. An accompaning bar screen and anti-vortex plate has the effect of reducing the tendency for vortices to form.

Suggestions for Further Research

Some factors such as the riser diameter and the distance from the bottom orifice relative to the side orifices of the riser were considered important in affecting the discharge. Further laboratory testing can be conducted for these factors to optimize the riser design. For more practical applications, additional research could be done to develop equations to describe the head-discharge relationship for other commercial types of risers and bottom orifice plates. Furthermore, a general equation could be developed mathematically.

The true head on the bottom orifice plate may not be significant for the field application, but it may be necessary for understanding from the standpoint of an investigator. As a starting point, a piezometer or pressure gauge can be used to determine the pressure head.

In the field, the plugging of the riser with floating residues may significantly decrease the discharge capacity. These are necessary concerns when developing design criteria. Laboratory testing would be the initial approach to the understanding of these effects. One could simulate the field condition and introduce different kinds and amounts of field debris to test for the head-discharge relationships. However the experimental work may be rather complicated.

In addition to the bar screen, there are some other accessories commonly used with risers, such as the commercial adjustable bottom orifice and the head control stand. The investigation could be extended to these applications.

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APPENDIX

Table 9. Data for 102-mm Spacing, Round Hole Riser without Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
181	95	0.578	3.9
186	95	0.578	3.9
207	99	0.578	4.3
210	101	0.578	4.5
215	103	0.578	4.8
222	106	0.578	5.1
238	110	0.578	5.6
271	117	0.578	6.5
287	119	0.578	6.8
309	124	0.578	7.5
352	135	0.578	9.3

Table 10. Data for 102-mm Spacing, Round Hole Riser with 89-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient	Weir Discharge (L/s)
56	57	0.578	1.1
59	58	0.578	1.2
113	71	0.578	1.9
127	80	0.578	2.6
162	89	0.578	3.3
215	99	0.578	4.3
249	109	0.578	5.5
312	118	0.578	6.7
335	125	0.578	7.7
384	131	0.578	8.7
387	132	0.578	8.8
427	137	0.578	9.7

Table 11. Data for 102-mm Spacing, Round Hole Riser with 64-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
41	56	0.578	1.1
59	60	0.578	1.3
87	61	0.578	1.3
110	65	0.578	1.5
123	79	0.578	2.5
182	90	0.578	3.4
243	99	0.578	4.3
353	102	0.578	4.7
523	116	0.578	6.4
778	126	0.578	7.9

Table 12. Data for 102-mm Spacing, Round Hole Riser with 38-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
20	41	0.578	0.5
30	50	0.578	0.8
44	55	0.578	1.0
118	62	0.578	1.4
135	63	0.578	1.4
138	64	0.578	1.5
178	66	0.578	1.6
235	69	0.578	1.8
264	70	0.578	1.8
319	71	0.578	1.9
442	77	0.578	2.3

Table 13. Data of 64-mm Spacing, Round Hole Riser without Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
34	62	0.578	1.4
76	79	0.578	2.5
105	91	0.578	3.5
157	111	0.578	5.7
198	123	0.578	7.4
237	134	0.578	9.2
268	144	0.578	11.0
293	150	0.578	12.1
325	159	0.578	14.0
334	162	0.578	14.7
378	173	0.578	17.3
488	199	0.579	24.5

Table 14. Data for 64-mm Spacing, Round Hole Riser with 89-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
25	41	0.578	0.5
27	43	0.578	0.6
95	77	0.578	2.3
180	107	0.578	5.2
270	128	0.578	8.2
393	144	0.578	11.0
581	155	0.578	13.1

Table 15. Data of 64- mm Spacing, Round Hole Riser with 64-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
49	55	0.578	1.0
92	75	0.578	2.2
118	83	0.578	2.8
131	85	0.578	3.0
193	96	0.578	4.0
223	100	0.578	4.4
326	107	0.578	5.2
425	113	0.578	6.0
559	119	0.578	6.8

Table 16. Data for 64-mm Spacing, Round Hole Riser with 38-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
28	45	0.578	0.6
52	56	0.578	1.1
137	64	0.578	1.5
165	66	0.578	1.6
197	67	0.578	1.7
288	71	0.578	1.9
367	74	0.578	2.1
715	88	0.578	3.2

Table 17. Data for Open-top Riser with 38-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
12	56	0.578	1.1
14	59	0.578	1.2
21	62	0.578	1.4
40	73	0.578	2.0
73	76	0.578	2.2
220	81	0.578	2.6
284	84	0.578	2.9

Table 18. Data for Open-top Riser with 64-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
5	54	0.578	1.0
22	64	0.578	1.5
42	78	0.578	2.4
49	89	0.578	3.3
54	101	0.578	4.5
56	103	0.578	4.8
61	113	0.578	6.0
130	117	0.578	6.5
191	120	0.578	7.0
415	130	0.578	8.5

Table 19. Data for Open-top Riser with 89-mm Orifice Plate

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
13	58	0.578	1.2
47	87	0.578	3.1
64	119	0.578	6.8
73	137	0.578	9.7
78	149	0.579	11.9
86	152	0.579	12.5
195	158	0.579	13.8

Table 20. Data for Slotted Riser

Riser Depth (mm)	Weir Depth (mm)	Weir Discharge Coefficient Ce	Weir Discharge (L/s)
81	59	0.578	1.2
102	67	0.578	1.7
130	76	0.578	2.3
159	85	0.578	3.0
195	95	0.578	3.9
270	115	0.578	6.3
292	120	0.578	7.0
304	123	0.578	7.4
347	132	0.578	8.8
371	138	0.578	9.9
387	138	0.578	10.4
395	143	0.578	10.8

HYDRAULICS OF TERRACE INTAKE RISER WITH ORIFICE PLATES

by

Jian Hua

B. S., National Taiwan College of Marine Science and Technology, 1980

AN ABSTRACT OF MASTER'S THESIS

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MASTER OF SCIENCE

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KANSAS STATE UNIVERSITY
Manhattan, Kansas

1987

ABSTRACT

Many terrace systems use underground pipe outlets instead of waterways. For economic reasons, bottom orifice plates are often used in combination with inlet risers. Laboratory analyses of head-discharge relationships for various riser-orifice plate combinations are needed.

Risers and orifice plates were fabricated from 147-mm (6-in.) diameter clear cast acrylic tubing and 6-mm (1/4-in.) thick acrylic sheet, respectively. Depth-discharge data were measured for each riser-orifice plate combination. Three sizes, 89 mm, 64 mm, and 38 mm (3.5 in., 2.5 in. & 1.5 in.) bottom orifice plates were tested in combination with each of four risers. Equations were constructed based on the hydraulic analyses of drop-inlet spillway to fit the experimental data.

Two existing equations for riser design were evaluated by fitting the experimental data of circular hole risers and slotted riser without using an orifice plate. The discharges of two 25.4-mm (1-in.) round hole risers are closely approximated by Equations 8 with a discharge coefficient of 0.75. Equation 8 also accurately estimates the discharge for the 25x102 mm (1x4 in.) slotted riser with a discharge coefficient of 0.60.

The open-top riser tends to introduce vortex and yield non-continuous discharging. The accompanied bar screen and anti-vortex plate have the effect of tranquilizing the turbulent flow and improving the discharge.